Army Research Laboratory

Structural Design and Analysis of Initial Extended Area Protection and Survivability (EAPS) Projectile Configurations

by Michael M. Chen

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14. ABSTRACT

A mission program named Extended Area Protection and Survivability was initiated at the U.S. Army Research Laboratory to demonstrate guided ammunition technologies to defend the battle space against any presented targets, such as mortars, rockets, and artillery. This report introduces the first step in the development of the guided ammunition system. It presents high-level physics-based simulations of a 60-mm projectile system. The topology of the initial projectile was developed on the basis of gun barrel specifications and certain aerodynamics characteristics. A three-dimensional finite element model was created to present the projectile system. Three different projectile configurations were analyzed with the LS-DYNA[1] program and the results were compared. An acceptable deign demonstrated that the muzzle velocity reached only 85% of target value mainly because the launch package exceeded the desired mass by 25%. In addition, a characteristic centerline variation of a gun barrel was taken into account in this report. The outcome of the in-bore vertical displacements and accelerations attributable to the variation was found to be significant. Note that the structural configuration of the initial projectile is not optimal. Rigorous optimization efforts will be made on the system, particularly on the sabot component, in order to meet performance requirements.

[1]LS-DYNA, which is not an acronym, is a trademark of Livermore Software Technology Corporation.

15. SUBJECT TERMS

barrel centerline variation; EAPS projectile; in-bore dynamics; 60-mm projectile

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[1]BAE is not an acronym.

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1. Introduction

Research in high-supersonic guided projectiles that intend to intercept incoming missiles has been of interest in recent years. Examples, such as in-bore dynamic responses of projectiles to two distinct types of propellants, validation of steering forces generated by control pins for medium caliber munitions, cavity design around fin area to achieve desired aerodynamic forces, enhancements in embedded electronics for better guidance, etc., are available in the literature (*1 through 4*). The U.S. Army Research Laboratory (ARL) initiated a program named Extended Area Protection and Survivability (EAPS) to investigate guided ammunition technologies to defend the battle space against any presented targets. The ultimate goal is to develop and demonstrate critical supporting technologies, including interceptor, sensor and fire controls, to enable stationary/mobile 360-degree hemispherical extended area protection from direct and indirect fire. This report presents the very first step for the development of the mission program, which is to perform preliminary structural design and analysis for the launch package. The guided ammunition system was designed to hit and destroy hostile objects, such as mortars, rockets, and artillery. The whole process must be undertaken with high accuracy at an extended range in a very short time frame. The launch package of study that supports the mission includes all payload, sabot, and projectile. With high launch acceleration, interactions among these components must be understood. The focus of the report falls on the design of the projectile system so that the structural integrity can hold during the launch.

The topology of the initial EAPS projectile was designed on the basis of gun barrel specifications and certain aerodynamic characteristics. A drawing from the Projectile Design and Analysis System (PRODAS) software provided by Arrow Tech Associates, Inc., depicted the outer configuration of the projectile. The detailed information of the initial configuration is given in the appendix A. The drawing was thereafter transformed into a solid model as shown in figure 1. The projectile is equipped with a windscreen and a penetrator in the front, having an ogive length and radius of 70.5 mm and 1,380 mm, respectively. Four fins for stabilization are embedded in the tail with a fin span of 50 mm. Detailed fin configuration that had no structural significance was ignored. The projectile has a total length of 316.7 mm from nose to tail and an outer diameter of 23.5 mm. The inside of its body is divided into two cavity areas. The forward cavity may carry high explosive payload while the rear cavity was designed to accommodate electronic equipments.

A 64-caliber smooth bore gun tube with an inner diameter of 60 mm was used to simulate the projectile firing. The detailed drawings of the gun barrel and the chamber specifications provided by the BAE Systems (formally United Defense Limited Partnership) are given in the appendix B. Note that all numbers on the drawings are in inches. The barrel has a total length of 3840 mm, i.e., in-bore travel distance for the projectile. M2 propellants with geometry of 7-perforation grain

were used for the propulsion. Considering a chamber volume of 1.3 liters, a peak breech pressure of 470 MPa was derived from the interior ballistics code IBHVG2 (interior ballistics of high velocity guns, version 2). Detailed IBHVG2 input parameter values and output data are given in the appendix C. With the assumption of the charge mass equivalent to that of the launch package, approximately 2/3 of the breech pressure would act on the projectile system. Based on the pressure level, the wall thickness of the projectile body was determined to be at least of 4 mm so that its hoop and radial stresses do not exceed yield strength. The results of the calculations served as a baseline for solid modeling and finite element analysis.

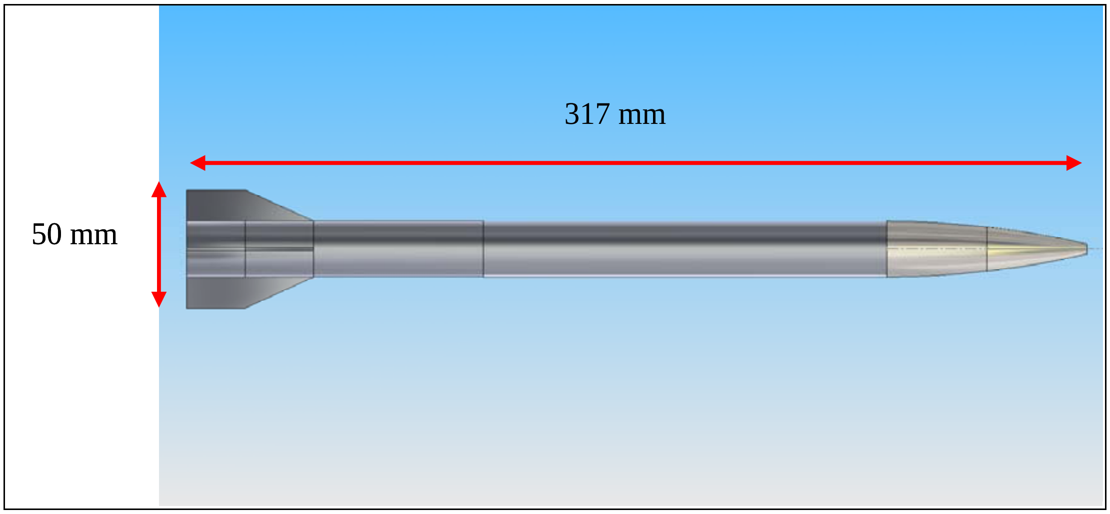

Figure 1. Configuration of the initial EAPS projectile.

Another major task of the study was to develop the sabot. Methodologies for forecasting sabot for projectile systems have been undergoing research for decades (*5,6*). The design of the sabot depends heavily on different types of propulsion systems. For a solid propellant gun, a conventional double-ramp sabot is appropriate. Typically, the purposes of sabot are to (a) support the projectile during high acceleration of launch; (b) guide the projectile along the center of gun barrel; (c) seal the gun tube to high-pressure propellant gas; and (d) discard smoothly after muzzle exit. It is understood that the length of sabot that supports a kinetic energy projectile is a major factor affecting the structural integrity. By applying limit state theorem, one can determine the fore and aft unsupported projectile length to avoid axial stress exceeding allowable value. A preliminary calculation suggested that the fore unsupported length could be included with the entire ogive area and the aft unsupported length with fin area. Grooves were designed for the interface between the sabot and projectile to handle a great deal of force transfer by means of equivalent shear stresses. The modeling of the grooves is not addressed in this report. Instead, a friction type of surface-to-surface contact was adopted in this study.

Please note that experimental validation will be performed at a later date to compare test results with simulation results. A preliminary design from this study will serve as a blueprint for the testing. To account for the influence of gun barrel centerline curvature, the gun tube to be used

must be measured. However, because the data were not available, the author employed a characteristic centerline variation provided by Dr. Bundy (*7*) in this study. The lateral displacement along down-bore distance from rear face of tube is shown in figure 2. For modeling feasibility, the curve was fitted with a high-order polynomial as shown. This report compares the velocity and stress responses of the characteristic gun with those of an ideally perfect straight barrel. Overall, the research was targeting a muzzle velocity of 1650 m/s with a total launch mass of 1 kg. A high launch acceleration of 82,000 to 95,000 acceleration-to-gravity ratio (g's) was pursued in the design.

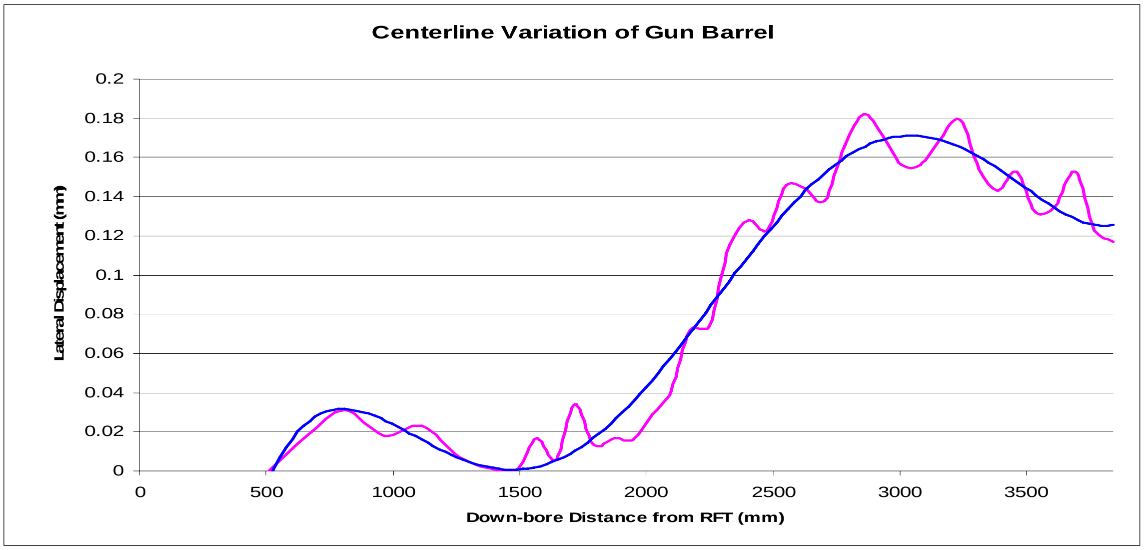

Figure 2. Characteristic centerline variation of a gun barrel.

2.   Modeling and Analysis

According to the design baseline, a three-dimensional (3-D) solid model was created. Figure 3 illustrates material configuration from a cross-sectional view of the projectile system. The sabot and windscreen cover were composed of 7075-T651 aluminum alloy, a high strength material that possesses a yield strength of 480 MPa. Tungsten with a 1240-MPa yield capacity was used for the penetrator. The gun barrel, projectile body, and fins were modeled with 17-4 PH[2] stainless steel (with H925 conditions treatment) that has a yielding strength of 1070 MPa. The space inside windscreen may accommodate an antenna and seeker. High explosive payload and the other electronics equipments may be mounted into the cavity area. Table 1 provides the physical and mechanical properties of each component. Based on the density property employed, the total mass of the projectile system was approximately 1.24 kg.

[2]17-4 PH is a registered trademark of AK Steel Corporation.

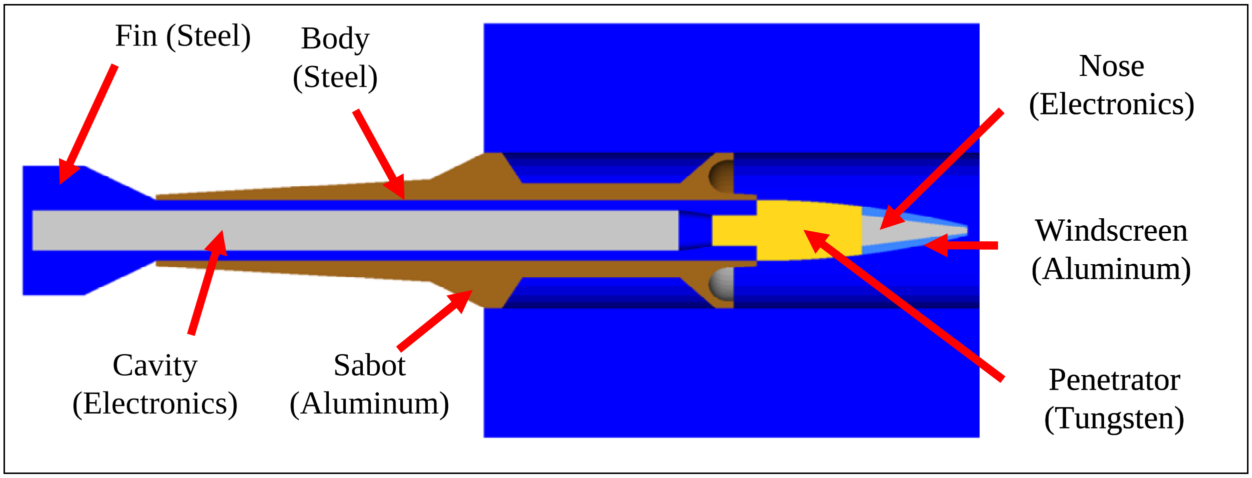

Figure 3. Material configuration of the initial EAPS projectile.

Table 1. Physical and mechanical properties of the initial EAPS projectile system.

Part No.	Part Name	Material	Density (kg/mm^3)	Elastic Modulus (MPa)	Poisson's Ratio	Weight (kg)
1	Bore	Steel	7.75E-06	1.96E05	0.28	-
2	Body & Fin	Steel	7.75E-06	1.96E05	0.28	5.03E-01
3	Penetrator	Tungsten	1.80E-05	3.65E05	0.28	2.71E-01
4	Windscreen	Aluminum	3.60E-06	6.90E04	0.33	9.51E-03
5	Sabot	Aluminum	3.60E-06	6.90E04	0.33	4.07E-01
6	Cavity	Electronics	7.10E-07	1.00E04	0.35	4.85E-02

As prescribed, the launch package consisted of projectile body, penetrator, windscreen, fins and sabot. A full-scale finite element model was generated to represent the projectile system, as shown in figure 4. All material throughout the model was assumed to be isotropic elastic material, i.e., material type 1 in LS-DYNA[3] (*8*). Constant stress property was specified for section solid elements. The model included a total of 237,232 8-node hexahedral elements and 231,456 nodes. Figure 5 displays time-dependent base pressure, which was derived from IBHVG2 output based on a 1.3-liter gun chamber and 1-kg launch mass. The duration of the pressure loading was 5 ms and the peak pressure of 335 MPa took place at 2.1 ms from the start of ignition. A load segment set was created as part of LS-DYNA key word file to include all surface elements in the chamber area. Subsequently, the load curve attribute of the segment set was linked to the base pressure curve, i.e., all surface elements subject to the pressure load.

It is important that the interfaces between bore-sabot, sabot-sabot and sabot-body be defined as contact surfaces in order to avoid element overlapping. LS-DYNA offers a variety of contact algorithms to treat interaction between disjoint parts. Surface-to-surface contact type was chosen for all the interfaces. Because the sabot moved along the in-bore surface, bore elements were defined as a master segment set type while the elements of bulkhead and bore-rider fell into slave

[3]LS-DYNA, which is not an acronym, is a trademark of Livermore Software Technology Corporation.

segments. The master-slave type can be arbitrarily chosen for sabot-sabot interfaces since no significance was found. The sabot-body interface was modeled as surface-to-surface contact as well. A high friction coefficient of 0.9 was assigned to simulate shear force transfer. In reality, grooves were designed to be responsible for the transfer but it was simplified in the simulation.

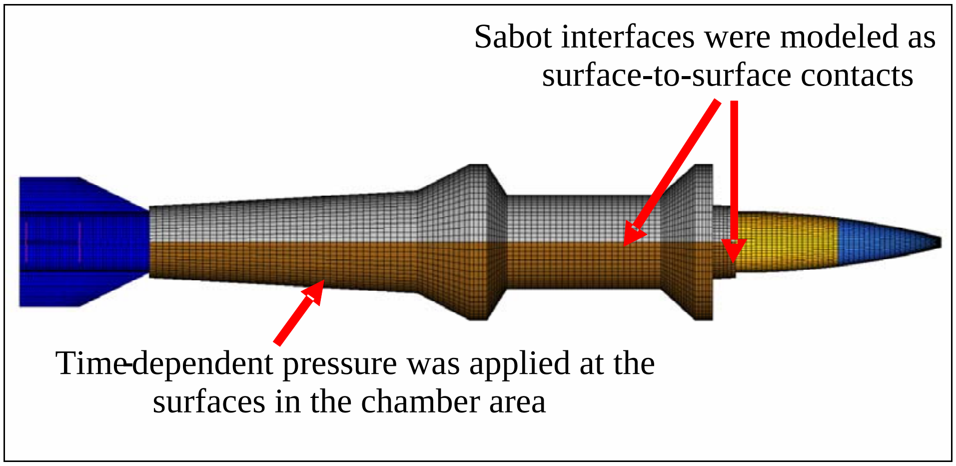

Figure 4. Presentation of finite element model.

Similarly, the bore-sabot interfaces were also represented by contact surfaces. To be precise, obturator would be the interfacing material. In this study, a number of different friction coefficients were used on the contact surfaces. Since the friction depends on the relative velocity and pressure between the two objects in addition to potential phase changes of obturator, the actual physics mechanism is rather complex. The sole intention of varying the attribute of the contact analysis was to look into the sensitivity of the results in response to various friction coefficients.

This report studied three different structural configurations for the EAPS projectile. Their descriptions are as follow: Case I: The body wall had a uniform thickness of 4 mm and the area between bulkhead and bore-rider of sabot was flat as given in figure 5. Case II: The wall thickness of the body was 5 mm in the front half and 4 mm in the tail portion. The rest remained the same as Case I, as demonstrated in figure 6. Case III: Sabot had a taper through the fore ramp and the other conditions stayed the same as Case I, as shown in figure 7.

Explicit dynamic analyses were performed with LS-DYNA tool on the Linux Networx Evolocity II cluster at the ARL Major Shared Resource Center. Each analysis took approximately 5 hours of central processing unit time on 16-thread parallel executions. LS-DYNA d3plot output files, a binary database, were requested at 0.1-ms intervals. From the result of the Case I analysis, it yielded a total of 5.0 ms in-bore travel time, as shown in figure 9. Note that the computed travel time was relatively longer than the applied pressure duration because the pressure was derived on the basis of 1-kg launch package mass, which was lighter than the model. Figure 10 displays in-bore travel velocity against travel time, which indicated that a muzzle velocity of approximately 1500 m/s was reached. The velocity curve was in line with the base pressure history, where the maximum slope took place at 2.1 ms after ignition. Since acceleration responses varied over the

entire model, an average number at the centers of the nose and the tail was used. The result shows a peak acceleration of 76 kilo-g's at 2.1 ms.

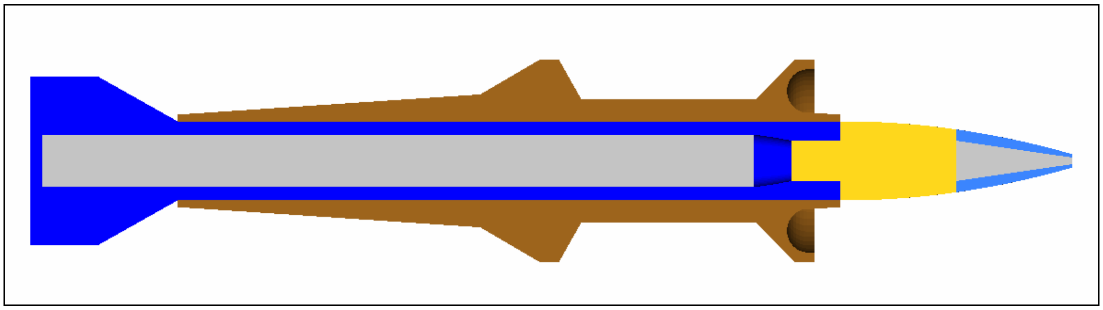

Figure 5. Case I structural configuration of the initial EAPS projectile.

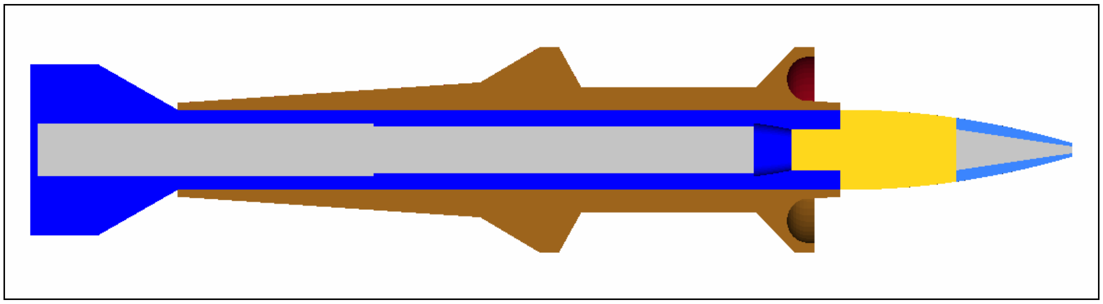

Figure 6. Case II structural configuration of the initial EAPS projectile.

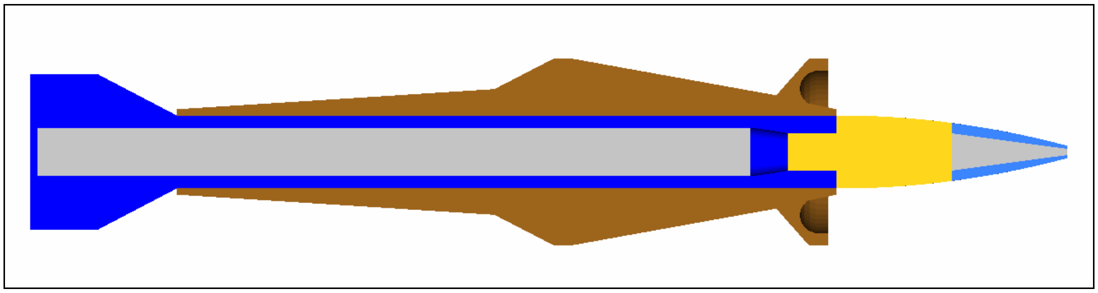

Figure 7. Case III structural configuration of the initial EAPS projectile.

The analytical results are summarized in table 2. The total weights of the launch package for Cases I, II, and III were 1.239 kg, 1.269 kg, and 1.375 kg, respectively. Given the loading history and duration of 5 ms as shown in figure 9, the Case I projectile traveled a distance of 3721 mm, close to the gun muzzle. The maximum acceleration of 76 kilo-g's took place at 2.1 ms from firing. Figure 11(a) displays contours of effective stress response in which a peak stress of 1210 MPa occurred at the projectile body area between bore-rider and bulkhead. It was obtained as a result of significant compression stress coming from the base pressure. Given 17-4 PH steel material, the Case I projectile would fail accordingly.

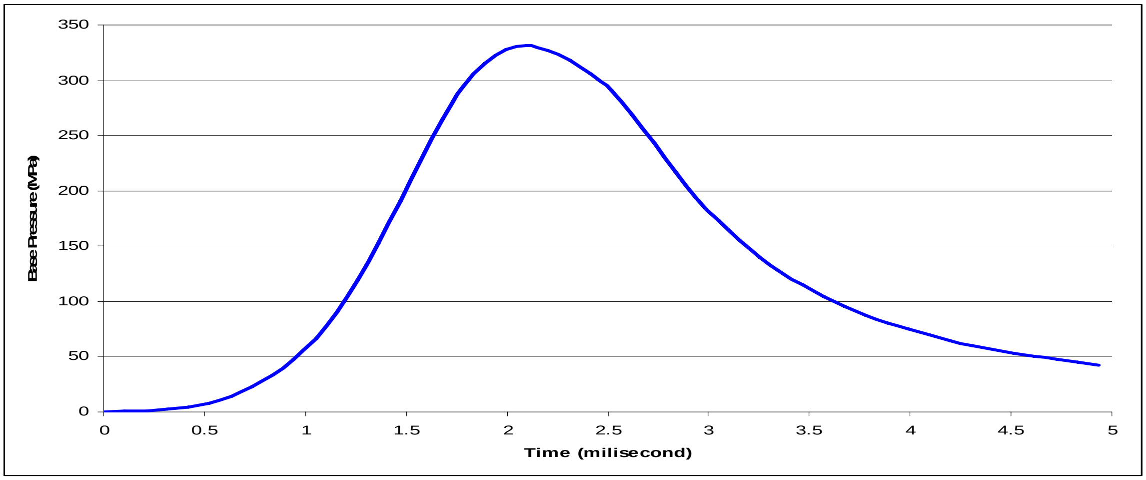

Figure 8. Time history of in-bore base pressure.

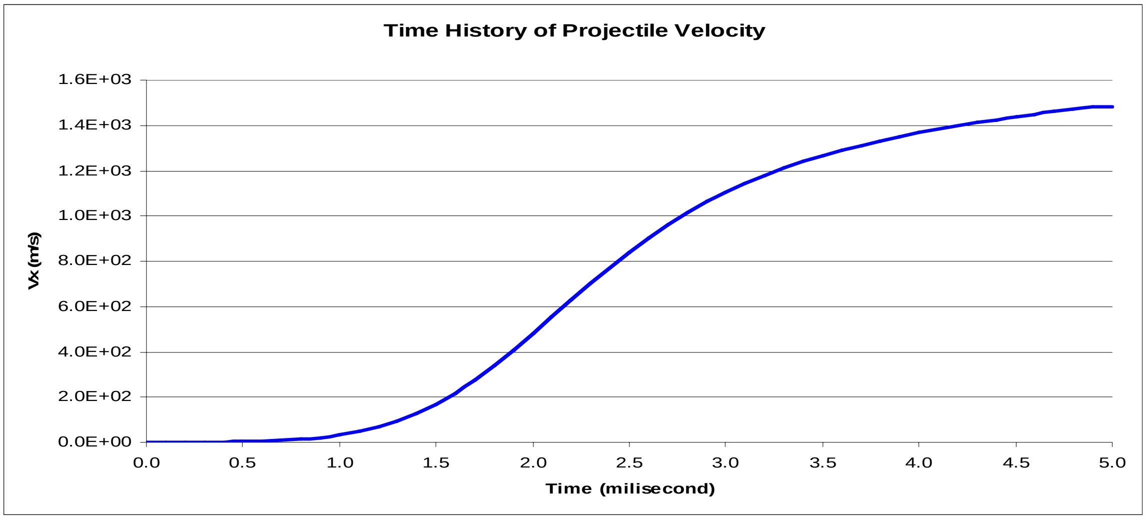

Figure 9. In-bore travel distance versus travel.

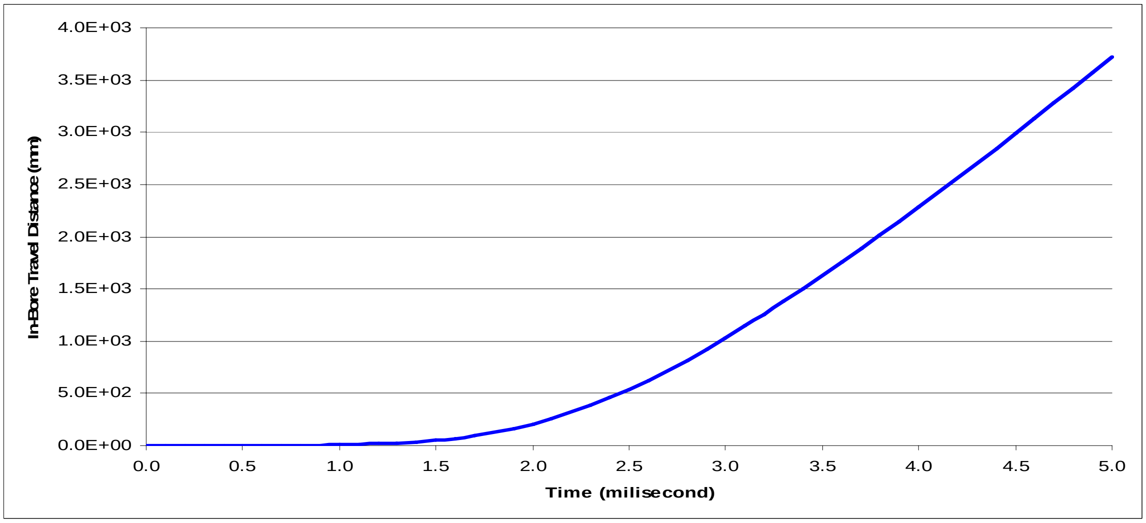

Figure 10. In-bore travel velocities versus travel time.

The Case II projectile, which increased the wall thickness by 1 mm, was developed to alleviate stress magnitude in the fore ramp area. Consequently, the peak stress was reduced to 985 MPa, as displayed in figure 11(b) contours. Because the maximum stress was below yielding strength, no permanent deformation was anticipated. However, because of the addition of mass by 30 g, the in-bore travel distance, peak velocity, and acceleration lowered to 3514 mm, 1398 m/s and 74 kilo-g's, respectively. In order to reach a target muzzle velocity of 1650 m/s, the breech pressure would need to be increased, which might result in re-adjustment of the structural configuration. Understandably, an iterative design and analysis process would be required.

Instead of increasing the wall thickness, the Case III augmented the sabot, i.e., it made the fore ramp go all the way to the bore-rider so that it could absorb more stress and obtain uniform stress response distributions because of increasing stiffness ratio between the sabot and projectile. The corresponding stress contours are shown in figure 11(c). The configuration changes resulted in a reduction of peak von Mises stress from 1210 MPa to 1035 MPa. The decrease in stress would prevent the steel material from yielding. Note that this alteration added significant mass to the launch system. The in-bore travel distance, peak velocity, and acceleration were all dropped to 3351 mm, 1345 m/s and 70 kilo-g's, respectively. Therefore, a trade-off was seen between free space for electronics and sabot mass.

Table 2. Responses of the initial EAPS projectile system to different weights of launch package.

	Case I	**Case II**	**Case III**
Total weight (kg)	1.239	1.269	1.375
In-bore travel distance (mm) at 5 ms from ignition	3721	3514	3351
Projectile velocity (m/s) at 5 ms	1492	1398	1345
Peak acceleration (kilo-g's) at 2.1 ms	76	74	70
Peak von Mises Stress (MPa) at 2.1 ms	1210	985	1035

Inside the projectile, the tungsten joint between the penetrator and body exhibited a high effective stress of 700 MPa, as shown in figure 12. However, the stress level was safely below its material strength. The disconnection area shown in the figure was a void inside the system. The aluminum windscreen and sabot are both subjected to pressure below yield strength. The encapsulation material and electronics appeared to have low and safe stresses as well. Because of the relatively long duration of pressure load, the effect of wave propagation was not significant.

To prevent the loss of propellant pressure during launch, an obturator was used to isolate the projectile from the bore of the gun barrel. Five different friction coefficients, i.e., 0.0, 0.1, 0.2, 0.3, and 0.5, for the sliding contact were used to investigate the influence on the exit velocity and stress responses. The results indicated that the differences in the responses among the coefficients of friction were marginal. However, the friction for the sabot-projectile interface must be sufficiently high in order to simulate force transfer and be able to move the projectile along. From simulation results, a coefficient of 0.5 is adequate.

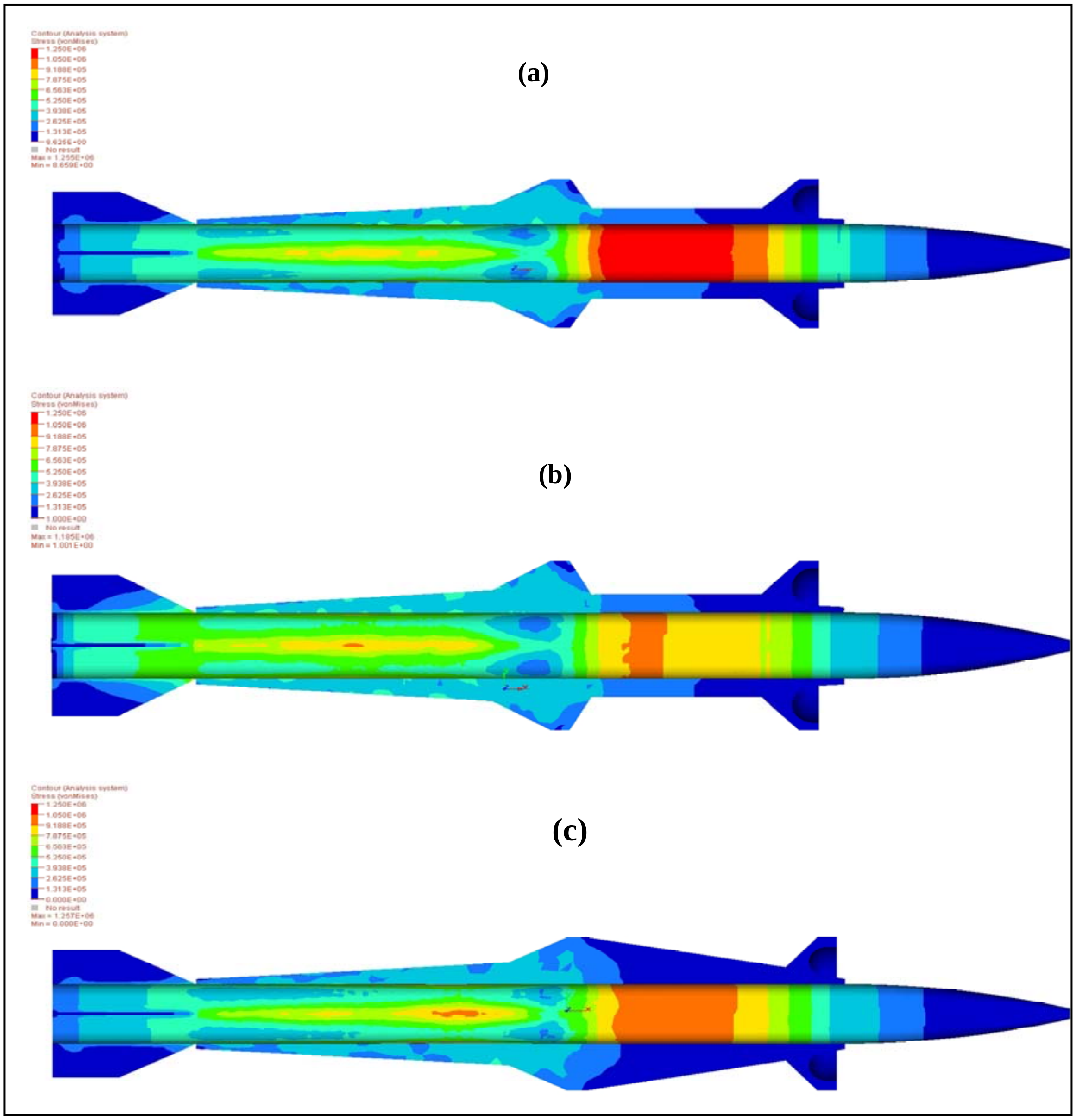

Figure 11. Contours of von Mises stress responses at 2.1 ms for (a) Case I, (b) Case II, and (c) Case III.

It is understood that the centerline curvature of a gun barrel influences the location of projectile shot impacts. In addition to investigating projectile response to configuration changes, this report also studied how the barrel with centerline variations would affect in-bore projectile movements. Two types of barrels, one with a perfectly straight centerline and another with characteristic centerline variation as provided in figure 2, were used. The Y movement (vertical plane perpendicular to axial direction) of the projectile at the nose while the projectile traveled in each barrel was captured and compared in figure 13. It can be seen that the projectile started balloting at 1.2 ms from ignition for both cases. However, after 1.8 ms, the blue line (the one with centerline variation) oscillated dramatically. The results indicated that in-bore Y displacement with centerline variation underwent as much as 0.22 mm, five times larger than that with the perfectly straight barrel.

Therefore, caution must be taken when one is considering gun manufacturing error since the muzzle exit yaw and pitch movements play a vital role in aerodynamic stability.

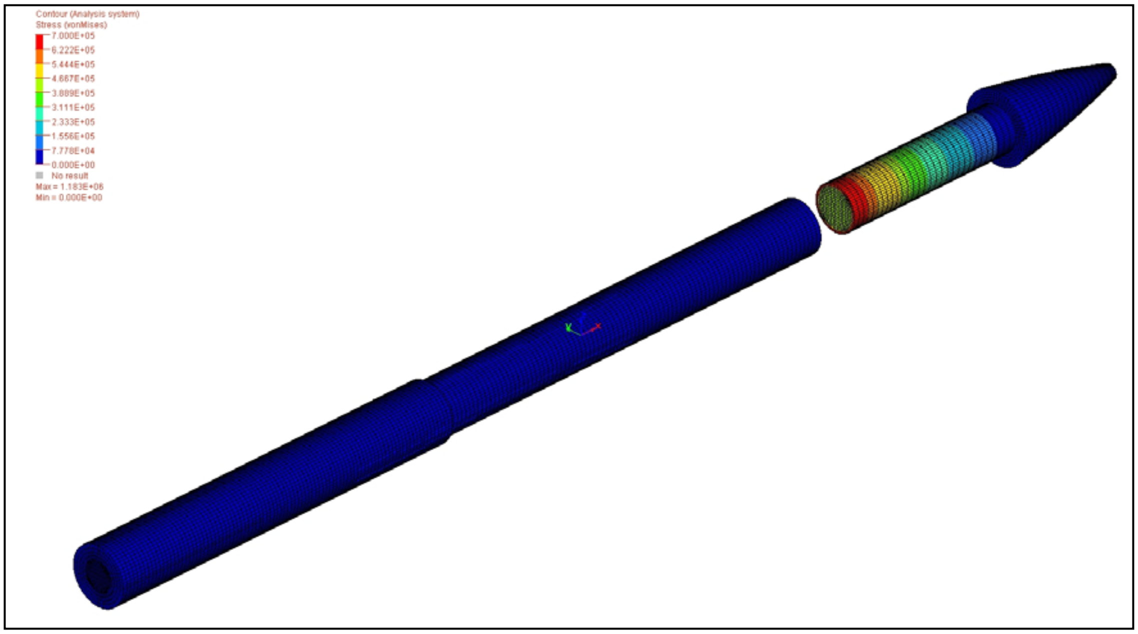

Figure 12. Effective stress responses of inner components.

Finally, the projectile system has been undergoing planning and development to possess a high probability of hit of 90%. This capability requires sophisticated guidance control to achieve high accuracy and to conduct the mission. Because of high acceleration launch, one must pay attention to the survivability of fragile electronics, such as seeker, antenna, transceiver, etc. It would not be possible for the projectile to accomplish its mission when any one of the components failed during launch. Furthermore, because of the centerline variations of a gun barrel, the electronics would be subject to extra vibrating accelerations. Figure 14 demonstrates in-bore vertical accelerations of the projectile with the characteristic gun barrel. It is shown that an acceleration as high as 26 kilo-g's may occur around 1.7 ms when the projectile started to deviate greatly from the centerline. Care must be taken in the analysis since the additional unanticipated loading may cause damage to the electronic equipment.

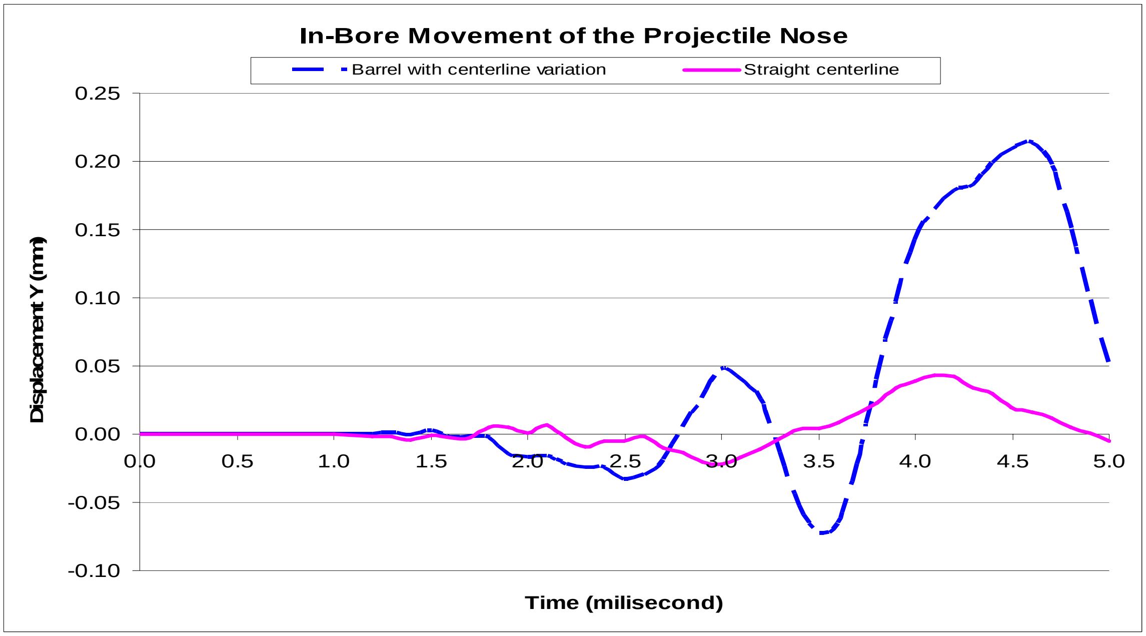

Figure 13. Comparison of in-bore movements with and without centerline variation.

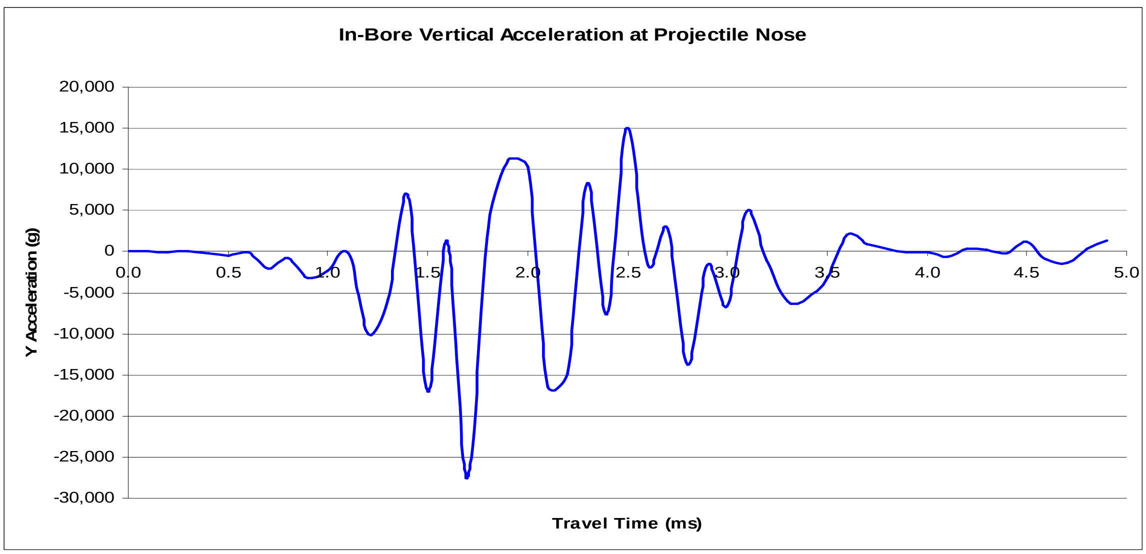

Figure 14. In-bore vertical accelerations versus travel time.

3. Summary

A mission program named EAPS was initiated to develop guided ammunition technologies to defend the battle space against any presented targets, such as mortars, artillery, and rockets. This report outlined a preliminary structural design and analysis of the initial EAPS projectile

configurations. It was the first step in the iterative development process of a guided ammunition system. The projectile launch package was intended to survive high g loading and to achieve high muzzle velocity. The development started with a pre-determined outer configuration, based on gun barrel specifications and certain aerodynamic characteristics. The system of the study included gun barrel, sabot, projectile body, tungsten nose, fin, and windscreen. A total of 22 components along with six different material properties were created and assembled for finite element analysis. The LS-DYNA computer code was employed to investigate the dynamics of the EAPS projectile. The simulation results will be validated by experimental tests that will be conducted later at ARL.

Three different configuration projectiles were studied and the results were compared. The projectile that had a uniform wall thickness of 4 mm with a flat fore ramp component was expected to encounter yielding failure. It would not survive the launch unless the sabot were altered so that it can transfer forces to the projectile body more uniformly. However, the alteration signifi-cantly increased the total mass of the launch package, which considerably impaired muzzle velocity. Alternatively, the author proposed to reinforce the projectile body by augmenting the thickness in the fore ramp area. As a result, the strength of the projectile was significantly improved and the integrity of the structure held. The muzzle velocity was not offset considerably. One negative influence from the change was slight reduction of free space. The free space could be designed to accommodate a warhead if applicable. Therefore, the actual impact would depend.

Note that the time-dependent breech pressure employed in this study was derived from IBHVG2 based on empty gun chamber and initially specified mass. On one hand, both factors exhibited certain degree of deviations from actual volume and weight in this study. More accurate measurements shall be undertaken. On the other hand, the lumped parameter code IBHVG2 assumed uniform and simultaneous ignition of the entire propellant charge. This unrealistic assumption has been relaxed by a complex computer program called the Next Generation (NGEN) Interior Ballistics code (*9*), which can account for multi-dimensional and multi-phase computational fluid dynamic physics problems. For continuing efforts in the EAPS projectile development, the incorporation of NGEN into the analysis becomes important.

The effects of centerline variations of a characteristic gun barrel on the initial EAPS projectile were also evaluated. It was found that the maximum in-bore vertical movement was five times larger than that for a gun barrel with a straight centerline. In addition, the vertical acceleration loads attributable to centerline curvature were substantial and may have a significant impact on the electronics. The actual gun barrel to be used for experimental firing would need to be carefully measured upon delivery. The actual variations would be used in later simulations for better prediction. Finally, the muzzle velocity from the study did not reach the target value. The total mass of the launch package required considerable reduction from the preliminary design. Rigorous optimization efforts will be made, particularly on the sabot component.

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Appendix A. Initial EAPS Projectile Configuration Data From PRODAS

Mod projectile1.pr3 - 0
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Mass2000 Version 3.0.0

	Mass	Transverse Inertia	Axial Inertia	CG from Nose	Diameter
	gm	gm-cm^2	gm-cm^2	cm	cm
Total Projectile:					
Baseline	687.2219	63103.87	571.3259	13.01830	
Calculated	687.2219	63103.87	571.3259	13.01830	
Launch Vehicle:					
Baseline	687.2219	63103.87	571.3259	13.01830	
Calculated	687.2219	63103.87	571.3259	13.01830	
Flight Vehicle:					
Baseline	687.2219	63103.87	571.3259	13.01830	2.350000
Calculated	687.2219	63103.87	571.3259	13.01830	2.350000

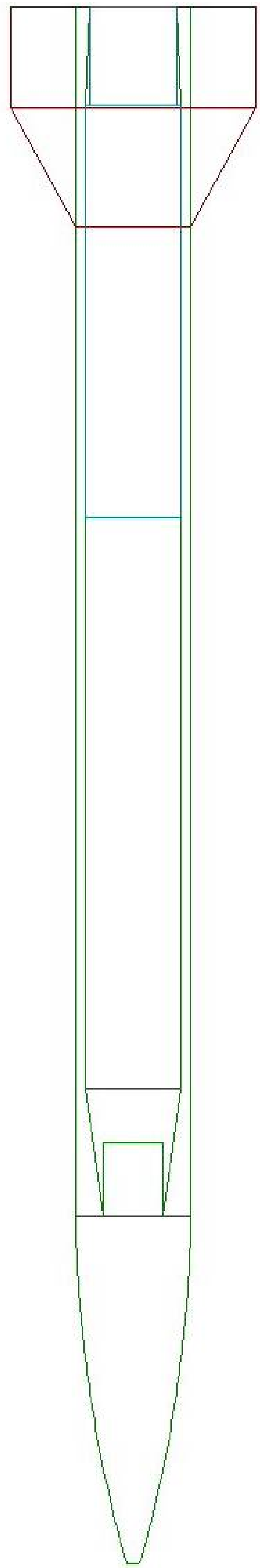
Calculated Aerodynamic Features of the Flight Vehicle (calculated values are used unless locked)

Calculated Values

Projectile Length	:	31.6656 cm
Ogive Length	:	7.0500 cm
Ogive Radius	:	27.9999 cm
Meplat Diameter	:	0.2800 cm
Boattail Length	:	0.0000 cm
Boattail Diameter	:	0.0000 cm
Boom Length	:	0.0000 cm
Boom Diameter	:	0.0000 cm
Rotating Band Length	:	0.0000 cm
Rotating Band Diameter	:	0.0000 cm

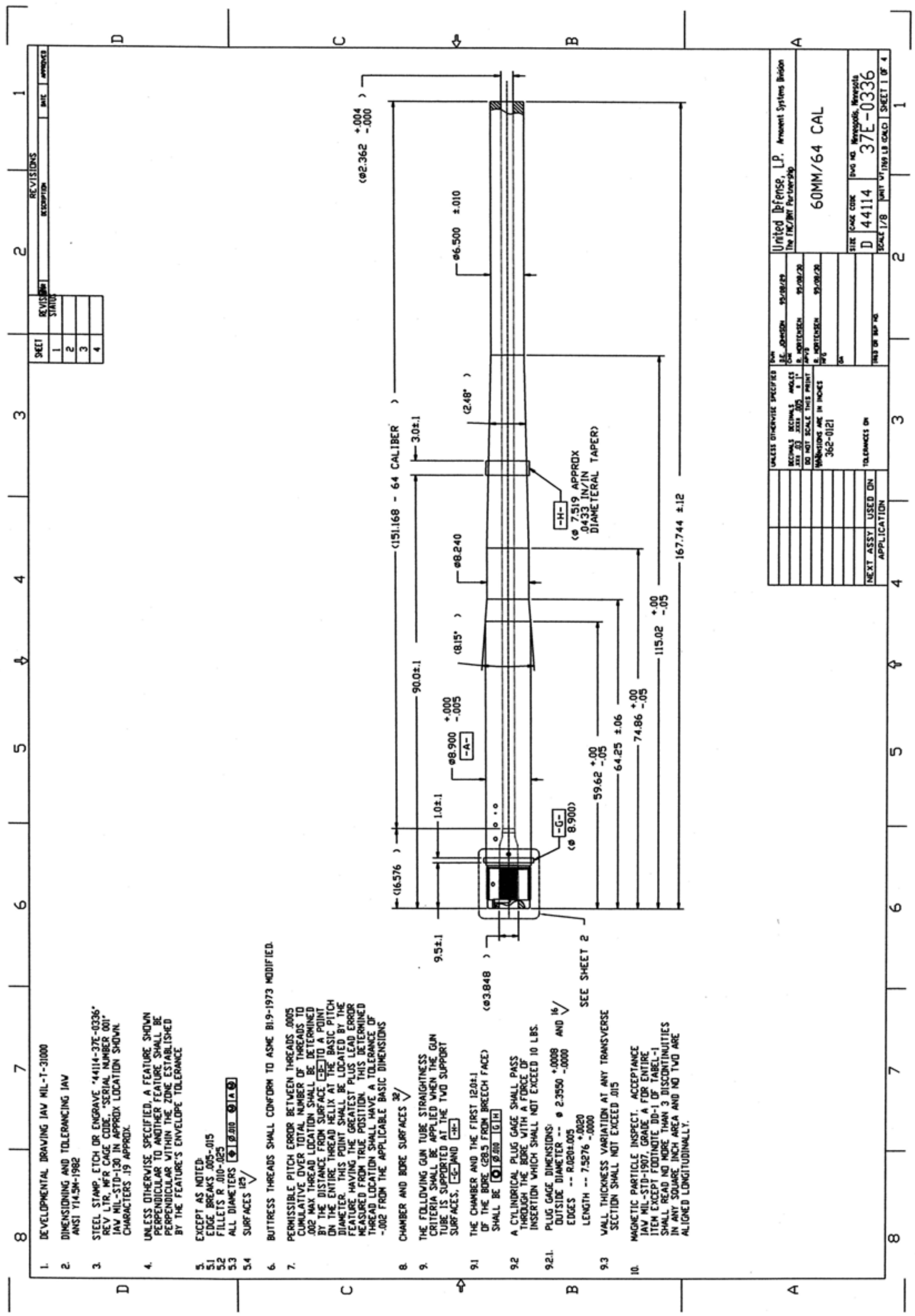
Mod projectile1.pr3 - 0
12/14/2005 14:25
Mass2000 Version 3.0.0

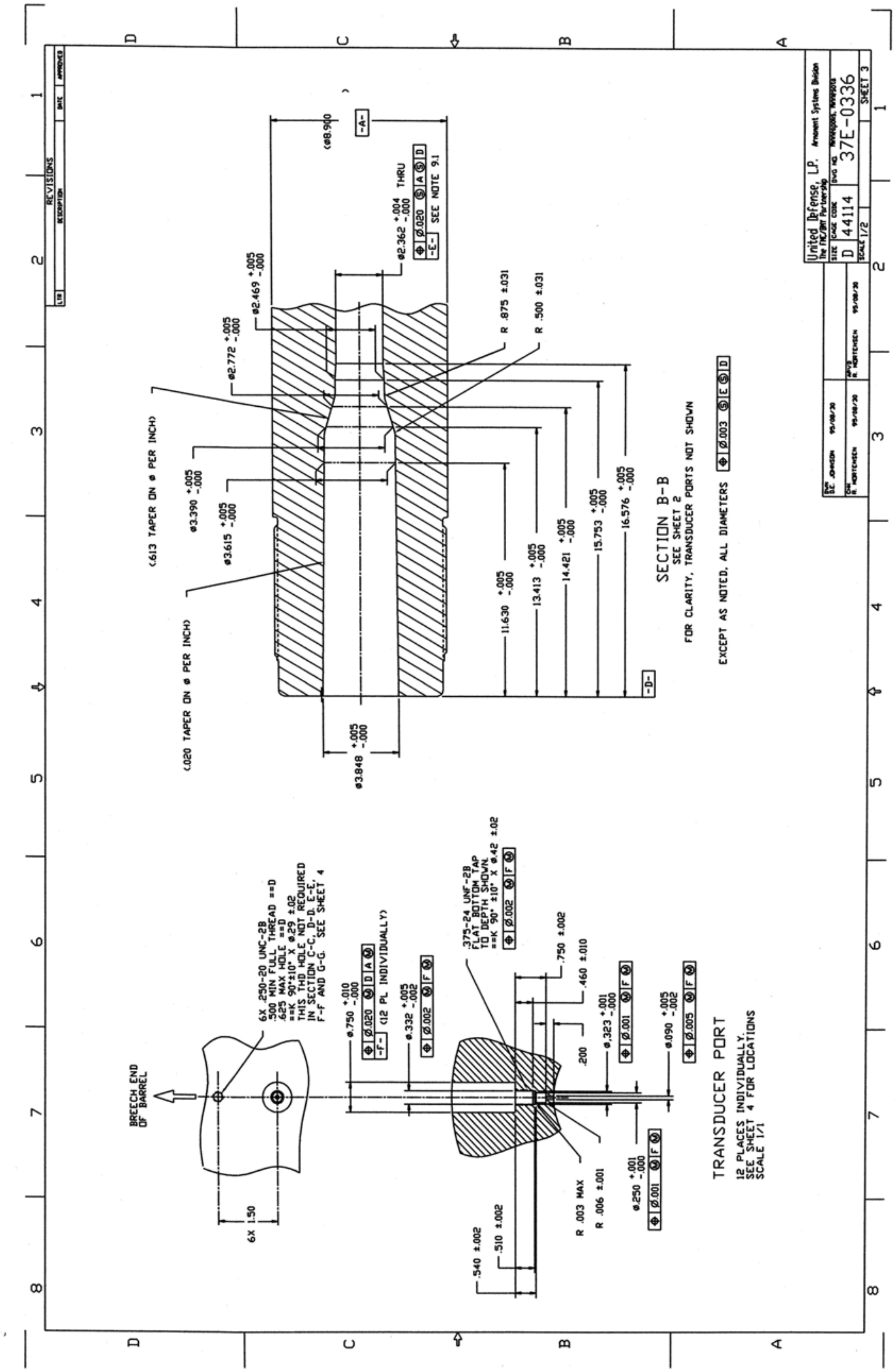
	Mass gm	Transverse Inertia gm-cm^2	Axial Inertia gm-cm^2	CG from Reference cm	Density gm/cm^3
Assemblies:					
Assembly	687.2219	63103.87	571.3259	18.64730	
Complete	687.2219	63103.87	571.3259	18.64730	
Components:					
Body	287.4107	16454.72	324.8266	12.97622	7.833000
Fins	20.34313	55.69299	65.57007	1.707554	7.833000
Penetrator	329.7155	1103.226	157.9962	11.16390	18.00000
Electronics	49.75256	444.7000	22.93301	5.306922	1.661000



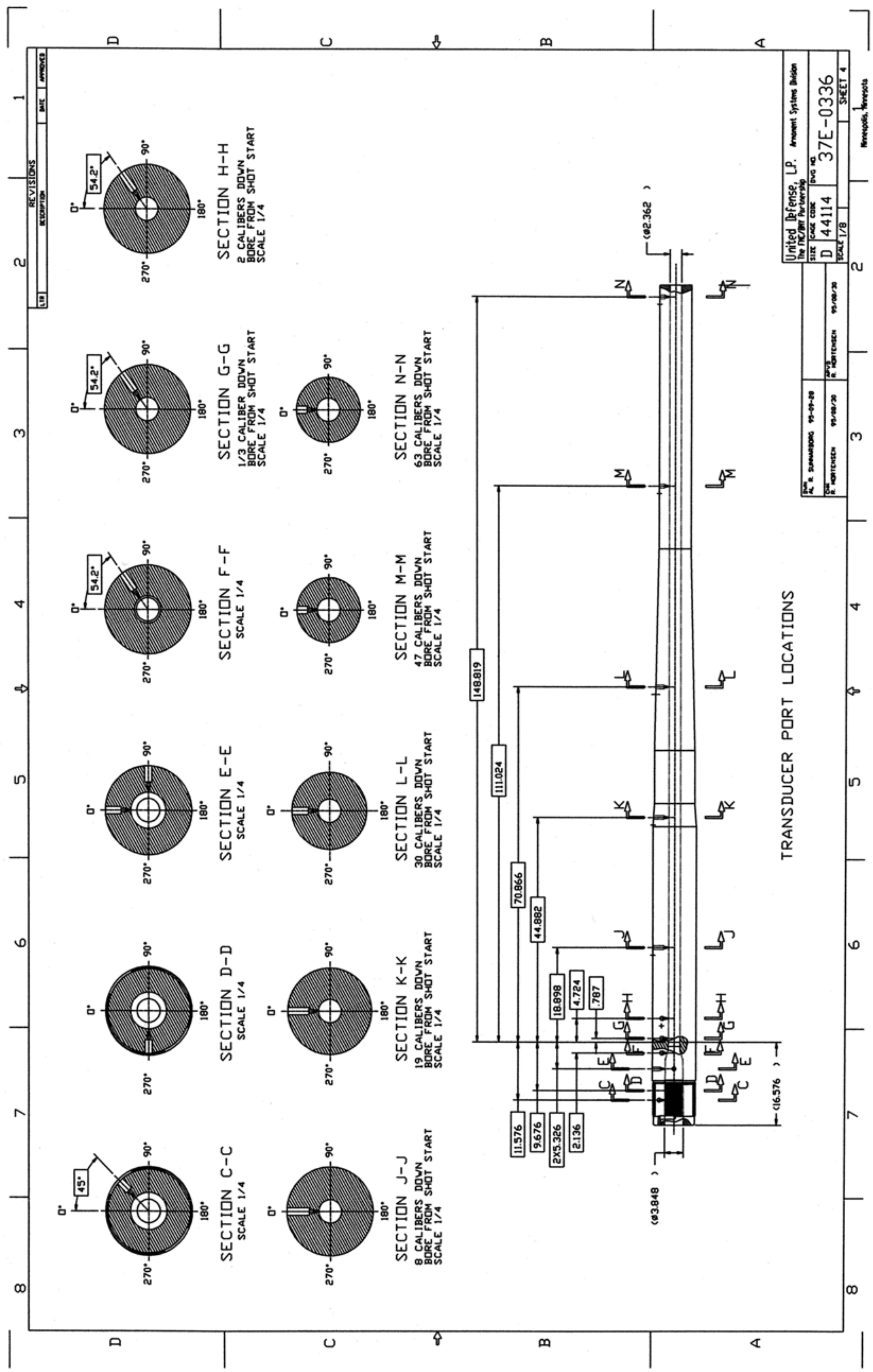
INTENTIONALLY LEFT BLANK

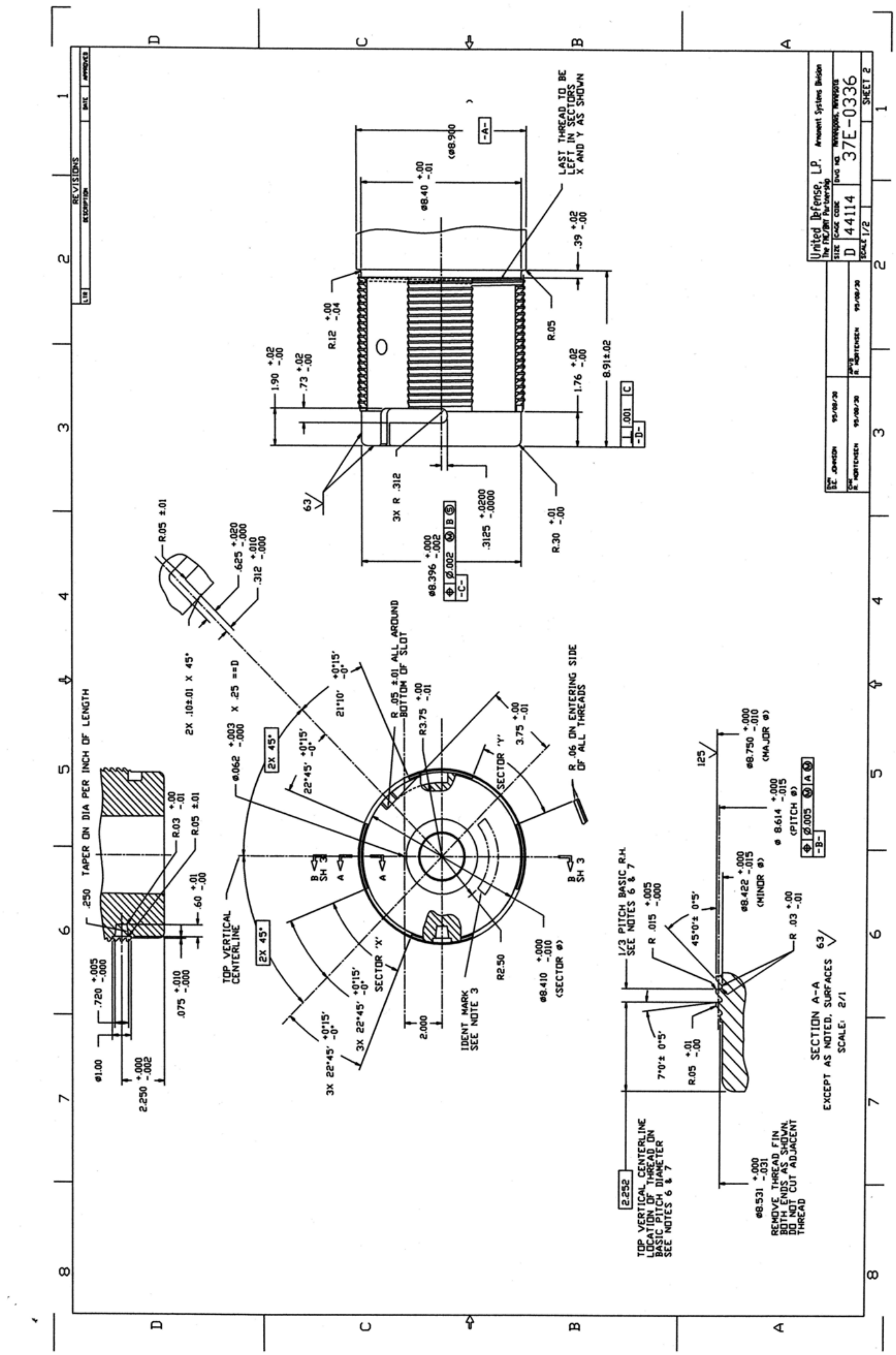
Appendix B. Gun Barrel Specifications





REVISIONS
SECTION B-B
SEE SHEET 2
FOR CLARITY, TRANSDUCER PORTS NOT SHOWN
EXCEPT AS NOTED, ALL DIAMETERS
TRANSDUCER PORT
12 PLACES INDIVIDUALLY.
SEE SHEET 4 FOR LOCATIONS
SCALE 1/1
BREECH END
OF BARREL
(.613 TAPER ON ø PER INCH)
(.020 TAPER ON ø PER INCH)
SEE NOTE 9.1
6X .250-20 UNC-2B
.500 MIN FULL THREAD
.625 MAX HOLE
THIS THD HOLE NOT REQUIRED
IN SECTION C-C, D-D, E-E,
F-F AND G-G. SEE SHEET 4
(12 PL INDIVIDUALLY)
.375-24 UNF-2B
FLAT BOTTOM TAP
TO DEPTH SHOWN
R .003 MAX
6X 1.50
United Defense, L.P.
Armament Systems Division
D
44114
37E-0336
SHEET 3
SCALE 1/2


SECTION C-C
SCALE 1/4
SECTION D-D
SCALE 1/4
SECTION E-E
SCALE 1/4
SECTION F-F
SCALE 1/4
SECTION G-G
1/3 CALIBER DOWN
BORE FROM SHOT START
SCALE 1/4
SECTION H-H
2 CALIBERS DOWN
BORE FROM SHOT START
SCALE 1/4
SECTION J-J
8 CALIBERS DOWN
BORE FROM SHOT START
SCALE 1/4
SECTION K-K
19 CALIBERS DOWN
BORE FROM SHOT START
SCALE 1/4
SECTION L-L
30 CALIBERS DOWN
BORE FROM SHOT START
SCALE 1/4
SECTION M-M
47 CALIBERS DOWN
BORE FROM SHOT START
SCALE 1/4
SECTION N-N
63 CALIBERS DOWN
BORE FROM SHOT START
SCALE 1/4
45°
54.2°
148.819
111.024
70.866
44.882
18.898
4.724
.787
11.576
9.676
2X5.326
2.136
(Ø3.848)
(16.576)
(Ø2.362)
TRANSDUCER PORT LOCATIONS
United Defense, L.P.
Armament Systems Division
D
44114
37E-0336
SCALE 1/8
SHEET 4
REVISIONS



REVISIONS
United Defense, L.P.
Armament Systems Division
D
44114
37E-0336
SCALE 1/2
SHEET 2
SECTION A-A
EXCEPT AS NOTED, SURFACES
SCALE: 2/1
TAPER ON DIA PER INCH OF LENGTH
TOP VERTICAL CENTERLINE
SECTOR 'X'
SECTOR 'Y'
IDENT MARK SEE NOTE 3
LAST THREAD TO BE LEFT IN SECTORS X AND Y AS SHOWN
R .06 ON ENTERING SIDE OF ALL THREADS
1/3 PITCH BASIC R.H. SEE NOTES 6 & 7
REMOVE THREAD FIN BOTH ENDS AS SHOWN. DO NOT CUT ADJACENT THREAD
TOP VERTICAL CENTERLINE LOCATION OF THREAD ON BASIC PITCH DIAMETER SEE NOTES 6 & 7

Appendix C. IBHVG2 Input Parameter Values and Partial Output Data

ERRTOL= 2.2204460E-16

1 IBHVG2.506 DATE TIME

0 CARD 1 --> $INFO

CARD 2 --> POPT = 1, 1, 1, 0

CARD 3 --> RUN = '57MM'

CARD 4 --> GRAD = 1

CARD 5 --> DELT=5E-6 DELP=1E-5

CARD 6 --> $GUN

CARD 7 --> NAME = '57MM'

CARD 8 --> GRVE = 0.060 LAND = 0.060

CARD 9 --> TRAV = 3.84 TWST = 99.0000

CARD 10 --> CHAM=0.001007

CARD 11 --> $PROJ

CARD 12 --> NAME = 'SLUG' PRWT = 1.2

CARD 13 --> $RESI

CARD 14 --> NPTS = 4 AIR = 1

CARD 15 --> TRAV = 0.0, 0.001, 0.02, 4.0

CARD 16 --> PRES = 2.0, 10.0, 1, 1

CARD 17 --> $HEAT

CARD 18 --> HL = 1

CARD 19 --> $PRIM

CARD 20 --> NAME = 'BENITE' CHWT = 0.00015

CARD 21 --> GAMA = 1.221 FORC = 548700.

CARD 22 --> COV = 0.0009747145 TEMP = 2041

CARD 23 --> $PROP

CARD 24 --> NAME = 'M30'

CARD 25 --> CHWT = 0.9

CARD 26 --> RHO = 1660. GAMA = 1.251

CARD 27 --> FORC = 1109000. COV = 0.001029

CARD 28 --> TEMP = 3118.0

CARD 29 --> GRAN = '7PF' LEN = 0.0047625 PD = 0.00029972

CARD 30 --> WEB = 0.00040

CARD 31 --> BETA = 0.002546

CARD 32 --> ALPH = 0.727

CARD 33 --> $COMM $PROP

CARD 34 --> NAME = 'JA2 7P' CHWT = 1 GRAN = '7P'

CARD 35 --> RHO = 1595.2 GAMA = 1.2268 FORC = 1150907.

CARD 36 --> COV = 0.0009747145 TEMP = 3436 EROS = 0.0000000

CARD 37 --> NTBL = -2 PR4L=68.96,700. CF4L=.003559,.0018033 EX4L=.7162,.8796

CARD 38 --> LEN = 0.004841 DIAM = 0.002146 PD = 0.000406

CARD 39 --> WEB=.00087

CARD 40 --> $COMM $PROP

CARD 41 --> NAME = 'M2' GRAN = '7PF'

CARD 42 --> CHWT = .86

CARD 43 --> RHO = 1650. GAMA = 1.2235

CARD 44 --> FORC = 1096000. COV = 0.000975

CARD 45 --> TEMP = 3373.0

CARD 46 --> LEN = 0.0048 PD = 0.0003

CARD 47 --> WEB = 0.0004728

CARD 48 --> BETA = 0.0019408

CARD 49 --> ALPH = 0.765

CARD 50 --> $PMAX

CARD 51 --> VARY='WEB' NTH=1 PMAX = 470. TRY1=.0004 TRY2=.00053 LOOP=60

CARD 52 -->

CARD 53 --> $COMM $PARA

CARD 54 --> VARY = 'CHWT' DECK = 'PROP' NTH = 1

CARD 55 --> FROM = .7 BY = .02 TO = .9

157MM IBHVG2.506 DATE TIME

0 CARD 56 --> $END

157MM IBHVG2.506 DATE TIME

- GUN TUBE -

TYPE: 57MM CHAMBER VOLUME (M3): 0.00101 TRAVEL (M): 3.84000

GROOVE DIAMETER (M): 0.06000 LAND DIAMETER (M): 0.06000 GROOVE/LAND RATIO (-): 0.000

TWIST (CALS/TURN): 99.0 BORE AREA (M2): 0.00283 HEAT-LOSS OPTION: 1

**WARNING: GROOVE/LAND RATIO .LE. 0., GUN TUBE IS ASSUMED TO BE SMOOTH-BORE OF DIAMETER 0.60000E-01

SHELL THICKNESS (M): 0.000102 SHELL CP (J/KG-K): 460.3163 SHELL DENSITY (KG/M3): 7861.0918

INITIAL SHELL TEMP (K): 293. AIR H0 (W/M**2-K): 11.3482

- PROJECTILE -

TYPE: SLUG TOTAL WEIGHT (KG): 1.200 WEIGHT PREDICTOR OPTION: 0

- RESISTANCE -

AIR RESISTANCE OPTION: 1 TUBE GAS INITIAL PRES (MPA) 0.000 WALL HEATING FRACTION: 0.000

RESISTIVE PRESSURE MULT INDEX: 3 RESISTIVE FACTOR 1.000 FRICTION TABLE LENGTH: 4

I TRAVEL (M) PRESSURE (MPA) I TRAVEL (M) PRESSURE (MPA) I TRAVEL (M), PRESSURE (MPA)

1 0.000 2.000 3 0.020 1.000 4 4.000 1.000

2 0.001 10.000

- GENERAL -

MAX TIME STEP (S): 0.000005 PRINT STEP (S): 0.000010 MAX RELATIVE ERROR (-): 0.00200

PRINT OPTIONS: 1 1 1 0 1 1 STORE OPTION: 0 CONSTANT-PRESSURE OPTION: 0

GRADIENT MODEL: LAGRANGIAN

- RECOIL -

RECOIL OPTION: 0 TYPE: RECOILING WEIGHT (KG): 0.

- PRIMER -

TYPE: BENITE GAMMA (-): 1.2210 FORCE (J/KG): 548700.

COVOLUME (M3/KG): 9.7471E-04 FLAME TEMP (K): 2041.0 WEIGHT (KG): 0.000150

157MM IBHVG2.506 DATE TIME

- CHARGE 1 -

TYPE: M30 GRAINS: 13936. 7PF WEIGHT (KG): 0.9000

EROSIVE COEFF (-): 0.000000 CHARGE IGN CODE: 0 CHARGE IGN AT (S): 0.00000E+00

GRAIN LENGTH (M): 0.004763 GRAIN DIAMETER (M): 0.003321 PERF DIAMETER (M): 0.000300

INNER WEB (M): 0.000605 OUTER WEB (M): 0.000605

PROPERTIES AT LAYER BOUNDARIES OF PERF SURFACES PROPERTIES AT LAYER BOUNDARIES OF END SURFACES

1ST 2ND 3RD 4TH 1ST 2ND 3RD 4TH

AT DEPTH (M): ------ ------ ------ 0.00000 ------ ------ ------ 0.00000

ADJACENT LAYER WT %: ------ ------ ------ 100.000 ------ ------ ------ 100.000

DENSITY (KG/M3): ------ ------ ------ 1660.000 ------ ------ ------ 1660.000

GAMMA (-): ------ ------ ------ 1.2510 ------ ------ ------ 1.2510

FORCE (J/KG): ------ ------ ------ 1109000. ------ ------ ------ 1109000.

COVOLUME (M3/KG): ------ ------ ------ 1.0290E-03 ------ ------ ------ 1.0290E-03

FLAME TEMP (K): ------ ------ ------ 3118.0 ------ ------ ------ 3118.0

BURNING RATE EXPS: ------ ------ ------ 0.7270 ------ ------ ------ 0.7270

BURNING RATE COEFFS: ------ ------ ------ 2.5460E-03 ------ ------ ------ 2.5460E-03

PROPERTIES AT LAYER BOUNDARIES OF LAT SURFACES

1ST 2ND 3RD 4TH

AT DEPTH (M): ------ ------ ------ 0.00000

ADJACENT LAYER WT %: ------ ------ ------ 100.000

DENSITY (KG/M3): ------ ------ ------ 1660.000

GAMMA (-): ------ ------ ------ 1.2510

FORCE (J/KG): ------ ------ ------ 1109000.

COVOLUME (M3/KG): ------ ------ ------ 1.0290E-03

FLAME TEMP (K): ------ ------ ------ 3118.0

BURNING RATE EXPS: ------ ------ ------ 0.7270

BURNING RATE COEFFS: ------ ------ ------ 2.5460E-03

.

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Lengthy time-history breech pressures are omitted here

.

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CONDITIONS AT: PMAX MUZZLE

TIME (MS): 1.522 4.712

TRAVEL (M): 0.1489 3.8400

VELOCITY (M/S) 440.85 1476.61

ACCELERATION (G): 81885. 7996.

BREECH PRESS (MPA): 470.0002 49.9707

MEAN PRESS (MPA): 427.3918 45.8103

BASE PRESS (MPA): 342.1750 37.4894

MEAN TEMP (K): 2749. 1565.

Z CHARGE 1 (-): 0.363 1.000

ENERGY BALANCE SUMMARY JOULE %

TOTAL CHEMICAL: 3976870. 100.00

(1) INTERNAL GAS: 1996360. 50.20

(2) WORK AND LOSSES: 1980510. 49.80

(A) PROJECTILE KINETIC: 1308220. 32.90

(B) GAS KINETIC: 327109. 8.23

(C) PROJECTILE ROTATIONAL: 659. 0.02

(D) FRICTIONAL WORK TO TUBE: 0. 0.00

(E) OTHER FRICTIONAL WORK: 11113. 0.28

(F) WORK DONE AGAINST AIR: 24479. 0.62

(G) HEAT CONVECTED TO BORE: 308930. 7.77

(H) RECOIL ENERGY: 0. 0.00

LOADING DENSITY (KG/M3): 893.893

CHARGE WT/PROJECTILE WT: 0.750

PIEZOMETRIC EFFICIENCY: 0.256

EXPANSION RATIO: 11.782

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1	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK TL 2800 POWDER MILL RD ADELPHI MD 20783-1197
2	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CS OK T 2800 POWDER MILL RD ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

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14	DIRECTOR US ARMY RSCH LABORATORY ATTN AMSRD ARL WM BC M BUNDY M CHEN (5 CYS) J DESPIRITO X HUANG R KEPPINGER P PLOSTINS J SAHU AMSRD ARL WM BD A BRANT AMSRD ARL WM MB W DRYSDALE M MINNICINO BLDG 4600